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Coulomb interactions within Halo EFT

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Abstract. I present preliminary results of effective field theory applied to nuclear cluster systems, where Coulomb interactions play a significant role.

1 Introduction

Nuclear systems far from the so-called valley of stability brought a lot of excitement to the field in the last years. While traditional approaches like shell model and mean field techniques provide qualitative descriptions of stable nuclei, they are seriously challenged by isotopes closer to either proton or neutron drip lines. The latter tend to form clusters loosely bound among themselves. Many of these isotopes, in particular halo nuclei, exhibit large cross-section at low energies, which can be quite relevant to reaction rates in nuclear astrophysics.

The weak binding of such cluster systems are usually well-separated from the next higher energy scale, for instance, the excitation energy of each cluster (nucleons and/or α particles). That turns out to be an attractive scenario for effective field theory (EFT) studies. The formalism takes into account only the relevant degrees of freedom at low momentum k and, according to a defined set of rules (power counting) provides a controlled and systematic expansion of physical quantities in powers of $k/M_{hi} \sim M_{lo}/M_{hi}$, where M_{lo} and M_{hi} set the magnitude of low and high momenta scales [1, 2].

Halo EFT was introduced in [6] with application to neutron-alpha scattering. Here I present applications of Halo EFT to alpha-alpha and proton-alpha systems, where Coulomb forces are important. These three basic interactions constitute the starting point for a description towards heavier nuclear systems.

2 $\alpha\alpha$ scattering

At low energies ($E_{LAB} \lesssim 3$ MeV) $\alpha\alpha$ scattering is dominated by S-wave and characterized by the existence of a resonance at $E_R = 184$ KeV and width

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$\mathit{\Gamma}_R = 11$ eV (the ^{8}Be ground state[1]). Analyses of scattering data using effective range theory reveal an incredibly large scattering length, $a_0 \sim 10^3$ fm [5], thus implying that our power counting needs more fine-tuning than naively expected. In [3] we developed a power counting for the $\alpha\alpha$, wich results in a very large scattering length, $a_0 \sim M_{hi}/M_{lo}^2$, and a non-perturbative (but still of natural size) effective range $r_0 \sim 1/M_{hi}$. Coulomb interactions were dealt non-perturbatively along the lines of [4] and the inverse of the amplitude becomes proportional to

$$-1/a_0 + r_0\, k^2/2 - 2H(\eta)/a_B \quad + \quad \text{subleading terms}\,, \tag{1}$$

where $a_B = 2/(m_\alpha Z_\alpha^2 \alpha_{em}) \approx 137/(2m_\alpha)$ is the $\alpha\alpha$ "Bohr radius", $\eta = (a_B k)^{-1}$ and $H(x) = \psi(ix) + (2ix)^{-1} - \ln(ix)$.

Interesting in this power counting is that, when Coulomb interactions are turned off, the third term of Eq. (1) becomes the usual unitarity term $-ik$, while the first two become subleading corrections. Therefore, at leading order the ^{8}Be system shows conformal invariance, and the corresponding 3-body system ^{12}C acquires an exact Efimov spectrum [2]. This is a possible realization of the unitarity limit. When Coulomb is restored, the $1/r$ potential breaks scale invariance and the three terms of Eq. (1) are of comparable size. However, the fact that the ^{8}Be ground state stays close to threshold can be seen as a reminiscence from this broken unitary regime.

We fit our EFT expressions to the available $\alpha\alpha$ scattering data (Fig. 1) and find agreement in the effective range parameters [5] except for a_0, whose inverse is very sensitive to big cancellations that occur between strong and electromagnetic contributions [3]. However, the order of magnitude is the same, which indicates a lot of fine-tuning in the $\alpha\alpha$ system that remains to be understood.

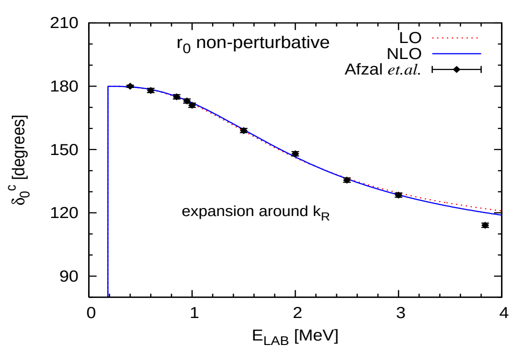

Figure 1. S-wave phase shift for $\alpha\alpha$ scattering as a function of the laboratory energy E_{LAB}.

3 $p\alpha$ scattering

In $p\alpha$ scattering one is interested in low-energies $E_{LAB} \lesssim 4$ MeV [7]. Phase shift analysis from [8] indicates that $S_{1/2}$, $P_{1/2}$, and $P_{3/2}$ are the dominant waves in this

[1] This resonance is quite relevant to the triple-α process, leading to the synthesis of ^{12}C in massive stars.

region, the latter showing a resonance around $E_{LAB} \sim 2.3$ MeV. We extended the formalism of [4] to include P-waves, and adopted the same power counting from Ref. [6], where the $P_{1/2}$ wave doesn't contribute up to NLO. Comparison with differential cross-section data from Ref. [9], using the effective range parameters from [8] as input, shows convergence and good agreement (Fig. 2).

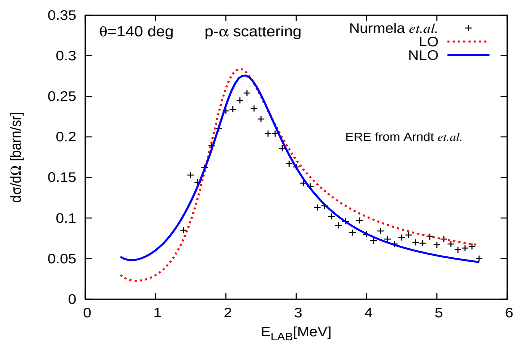

Figure 2. Differential cross-section for $p\alpha$ scattering as a function of the laboratory energy E_{LAB}, at fixed angle $\theta = 140°$.

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